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Short-term Effects of Applying Carboxylated Styrene Butadiene Emulsion-portland Cement Mixture on Road Base Construction

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ABSTRACT

The fundamental objective of this study is to understand the behavior and properties of the traditional and non-traditional additives and to characterize the cementitious stabilized base layer. This research presents experimental results on the improvement of short-term road base performance by the addition of carboxylated styrene butadiene emulsion (Rovene® 4045), portland cement and Rovene® 4045-portland cement mixture. To evaluate the short-term performance, the specimens were molded, cured for 7, 28 and 60 days and subjected to different stress sequences to study the Unconfined Compressive Strength (UCS), Indirect Tensile Strength (ITS), Indirect Tensile Resilient Modulus (ITRM), Flexural Strength (FS) and Unsoaked California Bearing Ratio (UCBR). The results indicate that the additives improved the strength and the stiffness of the specimens, which has been found to be an important quality indicator of mechanical properties of road base. The flexural strength tests showed that the addition of a 4% portland cement-7% Rovene® 4045 mixture resulted in improvements of 48.9% of modulus of rupture as compared to the sample with 4% cement. Therefore, this research nominates a new polymer additive having outstanding engineering properties.

Key words: Unconfined compressive strength, indirect tensile strength, indirect tensile resilient modulus, flexural strength, unsoaked California bearing ratio

INTRODUCTION

A variety of soils or granular materials are available for the construction of road bases but they may exhibit inadequate properties, e.g., low bearing capacity, susceptibility to moisture damage and susceptibility to environmental conditions, which would in turn result in substantial pavement distress and shortening of pavement life. However, the addition of a stabilizing agent can improve the properties of a soil-aggregate mixture. Among these different stabilizing materials, Cement Treated Base (CTB) develops significantly high stiffness and strength and exhibits good serviceability and high durability when used for pavement construction. Cement stabilization of soil was initiated on a trial basis in 1917 and since then, several works have been published on this topic (Sariosseiri and Muhunthan, 2009; Al-Amoudi *et al.*, 2010; Baghini *et al.*, 2013a, b; Ismail *et al.*, 2014). Polymer stabilizers are typically vinyl acetates or acrylic copolymers suspended in an emulsion by surfactants. The polymer stabilizer coats soil-aggregate particles and physical bonds are formed when the emulsion water evaporates, leaving a soil-polymer matrix. The emulsifying agent can also serve as a surfactant, improving penetration for topical applications and particle coating under admix conditions. The use of polymers as modifiers in new structures seems to be a promising strategy for improving the microstructure of mixtures and enhancing their durability (Fowler, 1999; Yang *et al.*, 2009). Polymers have a significant effect on the workability and mechanical properties of soil aggregate-cement mixture. The literature usually refers to the more commonly used styrene-butadiene polymer materials. These materials are known to possess superior durability over ordinary portland cement based concrete and are resistant to acid attack, ice melting and chloride diffusion. Several authors have shown that polymer impregnation of soil-aggregate cement materials may lead to increased durability depending on the type of polymers used. Previous studies have also indicated that the admixing of Styrene Butadiene Emulsion (SBE) latex into a mixture improved its resistance to chloride ion penetration (Pacheco-Torgal and Jalali, 2009; Li *et al*., 2010; Baghini *et al*., 2014). The molecular structure of SBE includes both flexible butadiene chains and rigid styrene chains, the combination of which lends many desirable characteristics to SBE-modified soil-aggregate cement materials, such as good mechanical properties, water tightness and abrasion resistance (Ohama, 1996; Shaker *et al*., 1997; Rossignolo and Agnesini, 2004; Wang *et al*., 2005). A Cement SBE Treated Base (CSBETB) can provide cost-effective solutions to many common designs and construction scenarios and impart additional strength and support without increasing the total thickness of the pavement layers. In addition, a stiffer base reduces deflections due to heavy traffic loads, thereby extending pavement life (Horpibulsuk *et al*., 2010; Perez *et al*., 2013). The CSBETB can also distribute loads over a wider area and reduce the stresses on the subgrade. It has a high load-carrying capacity does not consolidate further under load, reduces rutting in hot-mix asphalt pavements and is resistant to WD deterioration (Baghini *et al*., 2014). The goal of the present work was to assess the factors affecting the short-term performance of Cement-Rovene® 4045 Treated Base (CRTB) via laboratory tests. The short-term performance of stabilized soil-aggregate specimens was investigated by conducting UCS, ITS, ITRM, FS and UCBR, which are the most frequently employed factors for assessing the degree of road base stabilization. Another purpose was to determine the optimum of portland cement and Rovene® 4045 content.

MATERIALS AND METHODS

To achieve the goals of this study, a literature review, laboratory investigation and data processing and analyses were accomplished. To evaluate the short-term performance, the specimens were stabilized with portland cement (0-6%) and Rovene® 4045 (5-10%). The flowchart presented in Fig. 1 shows the framework of the research approach and experiment design of this study.

The soil-aggregate properties were evaluated prior to the design of the mixture and those physical and mechanical properties. Crushed granite aggregates from the Kajang Rock Quarry (Malaysia) were used as the granular base layer material in this study. Figure 2 illustrates the grading curve of soil-aggregates within the limits specified by American Society for Testing and Materials (ASTM) standards for highways and/or airports.

One of the most important factors affecting the performance of CTB is its organic content. In all probability, a soil with an organic content greater than 2% or a pH lower than 5.3 will not react normally with cement (ACI Committee 230, 1990). A mixture pH greater than 12.0 indicates that the organics present will not interfere with hardening (ARMY., 1994; Jones *et al.*, 2010). In this study, the results of a pH test conducted according to ASTM D 4972 indicated that adding cement alone to the soil-aggregate increased the pH from 8.26-12.13, whereas adding a cement-Rovene® 4045 mixture increased the pH from 8.26-12.67. This clearly shows that both types of additives have a positive effect, which we would state explicitly. The general properties of the soil-aggregates used in this study are summarized in Table 1 according to ASTM, American Association of State Highway and Transportation Officials (AASHTO) and British Standard (BS). Table 1 lists the most correlated geotechnical properties of the soil-aggregates used in this study.

In this study, type II portland cement was used as a treatment material for the granular mixtures because of its higher sulfate resistance, moderate heat of hydration and mostly equivalent cost in comparison to other types of portland cement. A high sulfate content of soil results in swelling and heaving problems and it can have a deleterious influence on cementing and stabilization mechanisms. The portland cement used in this study was required to conform to the respective standard chemical and physical requirements prescribed by ASTM C 150 and 114. The cement would be

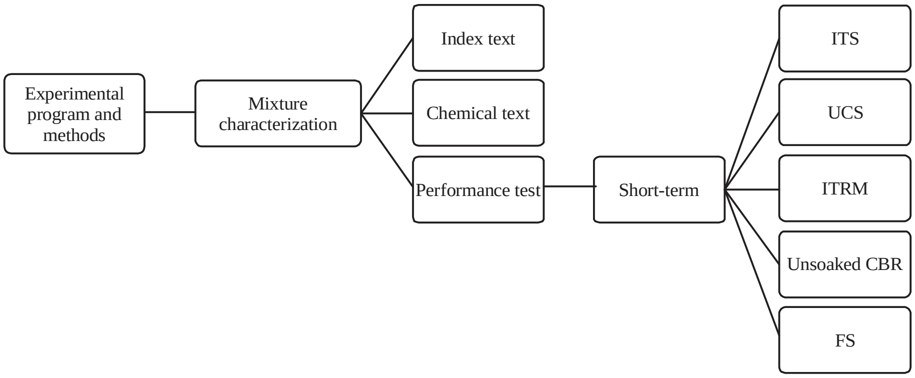

Fig. 1: Framework of the research approach and experiment design of this study

Table 1: Properties of soil aggregates used in this study

Property	Requirements	Test result	Test method
Water content (%)	NA	6.621	ASTM D 698
Unit weight (g cm^{-3})	NA	2.19	ASTM D 698
pH	5.3-Min.	8.26	ASTM D 4972
Unified classification	NA	GP-GM	ASTM D 2487
AASHTO classification	NA	A-1-a	ASTM D 3282/AASHTO M 145
Liquid limit (%)	25-Max.	21.4	ASTM D 4318
Plastic limit (%)	29-Max.	19.6	ASTM D 4318
Plastic index (%)	4-Max.	1.8	ASTM D 4318
Coefficient of curvature (Cc)	NA	2.39	ASTM D 2487
Coefficient of uniformity (Cu)	NA	71.5	ASTM D 2487
Group index	NA	0	ASTM D 3282
Specific gravity (OD)	NA	2.659	ASTM C 127/C 128
Specific gravity (SSD)	NA	2.686	ASTM C 127/C 128
Apparent specific gravity	NA	2.731	ASTM C 127/C 128
Water absorption (%)	2-Max.	0.973	ASTM C 127/C 128
Linear shrinkage (%)	3-Max.	1.5	BS 1377: Part 2
Elongation index (%)	25-Max.	13.03	BS 812: Section 105.2
Flakiness index (%)	25-Max.	7.68	BS 812: Section 105.1
Average least dimension (mm)	NA	5.5	BS 812: Section 105.1
Sand equivalent (%)	35-Min.	84	ASTM D 2419
Los Angeles abrasion (%)	50-Max.	17.5	ASTM C131
UCS (MPa)	NA	0.25	ASTM D 2166/D 1633
CBR (%)	80-Min.	101.32	ASTM D 1883

Max: Maximum, Min: Minimum, NA: Not applicable, ASTM: American society for testing and materials

Table 2: Properties of type II portland cement

Component and properties	Requirements (%)	Test result (%)	Test method
Silicon dioxide (SiO_2)	20-Min	20.18	ASTM C 150- C 114
Aluminum oxide (Al_2O_3)	6.0-Max	5.23	ASTM C 150- C 114
Calcium oxide (CaO)	NA	64.40	ASTM C 150- C 114
Ferric oxide (Fe_2O_3)	6.0-Max	3.34	ASTM C 150- C 114
Magnesium oxide (MgO)	6.0-Max	1.80	ASTM C 150- C 114
Sulfur trioxide (SO_3)	6.0-Max	3.03	ASTM C 150- C 114
Loss on ignition	3.0 -Max	2.17	ASTM C 150- C 114
Insoluble residue	0.75-Max	0.18	ASTM C 150- C 114
Na_2O	NA	0.07	ASTM C 150- C 114
K_2O	NA	0.44	ASTM C 150- C 114
Equivalent alkalies (Na_2O+0.658K_2O)	0.75-Max	0.3595	ASTM C 150- C 114
Tricalcium aluminate (C_3A)	8-Max	3.21	ASTM C 150- C 114
Tricalcium silicate (C_3S)	NA	53.95	ASTM C 150- C 114
Dicalcium silicate (C_2S)	NA	17.32	ASTM C 150- C 114
Tetracalcium alumino-ferrite (C4AF)	NA	10.16	ASTM C 150- C 114
Sum of (C_3S) and (C_3A)	58-Max	57.16	ASTM C 150- C 114
Compressive strength (MPa)			
3 days	10-Min	27.5	ASTM C 109/C 109M
7 days	17-Min	40.3	
28 days	28-Min	57.7	
Fineness, specific surface (m^2 kg^{-1})			
Air permeability test	280-Min	338.1	ASTM C 204
Autoclave expansion (Soundness)	0.8-Max	0.5	ASTM C 151

Max: Maximum, Min: Minimum, NA: Not applicable, ASTM: American society for testing and materials

rejected if it did not meet all of the necessary specifications. The properties of type II portland cement are presented in Table 2.

The mixing water used for these tests should be free of acids, alkalis and oils and in general, it should be suitable for drinking according to ASTM D 1632 and 4972. According to ASTD D1193, water is classified into 4 grades-types I, type II, type III and type IV depending on its physical, chemical and biological properties. All the mixed water used for these test methods should be ASTM type III or better. Water prepared by distillation is of type III, which is used in current study. Rovene® 4045 is a styrene-butadiene emulsion that provides soil aggregate binding strength and moisture resistance properties. It can be used in cases where stabilization of soil aggregate and binding are required. This material mostly used in road construction, landscaping, agriculture, dust control and erosion control applications. Rovene® 4045 provides good wetting of different types of soil aggregate, imparts dry and wet strength to the soil aggregates. The properties of Rovene® 4045 are presented in Table 3.

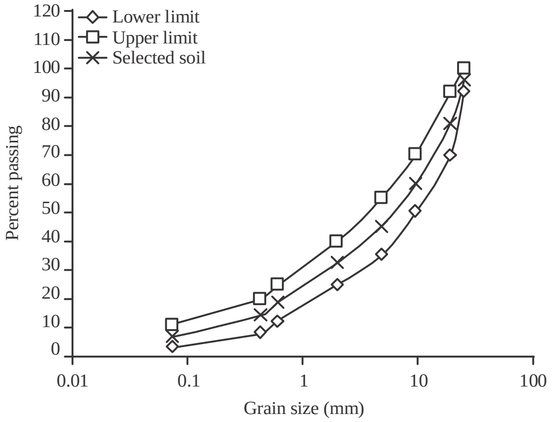

Fig. 2: Grading curves for soil aggregate

Table 3: Properties of Rovene® 4045

Chemical name	Carboxylated styrene butadine
Physical state	liquid
Boiling point	100°C at 17 mm Hg
Color	White, Milky
Solids content	45.0-45.7%
Vapor Density	1<
Vapor pressure	17 mm Hg at 20°C
Solubility in water	Miscible
pH	8.33
Specific gravity	1.00-1.03
Emulsifiers	Anionic
Viscosity (Brookfield #2/20 rpm)	900 max cps
Particle diameter	0.18 microns
Glass transition temp. (Tg)	+24°C
Water content (weight %)	53.54

EXPERIMENTAL PROCEDURES

Unconfined compressive strength: The primary purpose of the UCS test is to determine the approximate compressive strength of a mixture that has sufficient cohesion to permit testing in the unconfined state. For this test, the mixture was prepared according to ASTM D 1632 using a metal cylinder mould with an internal diameter of 101.60 mm and a height of 116.4 mm. The specimens were placed in the moulds in a moist room for 12 h for curing; subsequently, the specimens were removed using a sample extruder. The removed specimens were wrapped in plastic for protection against dripping water in the moist room at 25°C. Three specimens were fabricated for each percent of additive, resulting in 21 samples for portland cement (0-6%), 18 samples for Rovene® 4045 (5-10%) and 18 samples for the CRTB, respectively. The average UCS of the specimens cured for 7, 28 and 60 days was determined using a hydraulic compressive strength testing machine by applying a load at a constant rate within the range of 140±70 kPa sec^{-1} according to ASTM D 1633. Finally, the unit compressive strength (MPa) was calculated by dividing the maximum load (N) by the cross-sectional area (mm^2). It should be noted that, based on the previous studies and strength requirements for CTB, the optimum cement content was chosen as 4% (Al-Amoudi *et al*., 2010; Ismail *et al*., 2014).

Fig. 3: Indirect tensile strength testing setup

Indirect tensile strength: Indirect tensile strength may be used to evaluate the relative quality of a mixture in conjunction with laboratory mix design testing and to estimate the potential for rutting or cracking. The mixture was prepared according to ASTM D 1632 and ASTM D 6926 using a metal cylindrical specimen mould with an internal diameter of 101.60 mm and 63.5±2.5 mm height. The average ITS of the cement-treated specimens after 7, 28 and 60 days of curing time was obtained using a hydraulic compressive strength machine. According to ASTM D 6931 a vertical compressive ramp with a rate of 50 mm min^{-1} was applied until the maximum load reached. Equation 1 shows the calculation of ITS:

$$S_t = \frac{2 \times P}{\pi \times t \times D} \quad (1)$$

where, S_t is the ITS [MPa], P is the maximum load [N], t is the specimen height [mm] and D is the specimen diameter [mm]. Figure 3 shows the ITS testing apparatus and the ITS testing setup.

Resilient modulus of elasticity: The resilient modulus of a mixture, measured in the indirect tensile mode (ASTM D 4123), is the most popular form of stress-strain measurement used to evaluate elastic properties (Tayfur *et al*., 2007; Niazi and Jalili, 2009). The mixture for testing was prepared according to ASTM D 1632 and 6926 using a metal cylindrical specimen mold with an internal diameter of 101.60 mm and height of 63.5±2.5 mm. A repeated-load indirect tension test for determining the resilient modulus of each mixture was conducted according to ASTM D 4123 by applying compressive loads of 2000 N at 25°C with a waveform at 1.0 Hz for loading frequencies (the recommended load range can be 10-50% of the ITS). The resulting horizontal deformation of a specimen with an assumed Poisson's ratio of 0.2 was measured and five conditioning pulse counts were used to calculate the resilient modulus (ITRM). The values of horizontal deformation were measured using linear variable differential transducers (LVDTs). The LVDTs should be positioned at mid-height opposite each other along the specimen's diameter. Each specimen was tested twice for measurement of the ITRM. Following the first test, the specimen was rotated by approximately 90° and the test was repeated. Figure 4 shows the ITRM testing apparatus and the ITRM testing setup.

Flexural strength: The FS is considered a significant characteristic for pavement design and for determining slab thickness. FS is expressed as the modulus of rupture, which in this study was performed in accordance with the ASTM standard. ASTM D 1635 prescribes steps for determining the flexural strength of mixtures using a simple beam with three-point loading. In this study, the specimens were compacted into a metallic beam mold 76×76×290 mm and moist-cured, as explained in previous section. The average modulus of rupture of specimens cured for 7, 28 and 60 days was determined using a hydraulic testing machine. The test was conducted by applying a continuous load at a rate of 690±39 kPa min^{-1}. Three specimens were fabricated for each type of additive. Figure 5 shows the FS testing apparatus and the FS testing setup.

California bearing ratio: The CBR value is required for designing flexible pavement materials and thickness. In this research, the ASTM D 1883 test method was used to evaluate the potential strength of CTB and CTTB as a function of their CBR values. The specimens were compacted in five layers into a cylindrical metal mold with an inside diameter of 152.4 mm and a height of 177.8 mm to the MDD at OMC. The tests were performed for both soaked and unsoaked conditions. For soaked conditions, samples attached to a 4.54 kg steel weight were immersed in a water bath for four days to achieve suitable saturation. The initial and final measurements of swelling were taken before and after the 96 h soaking using a dial gage and the amount of swelling was calculated as a percentage of the initial height of the samples. The average CBR of the 7 days cured specimens was determined using a hydraulic compressive strength-testing machine by applying a load at a rate of 1.27 mm min^{-1}. The load readings were recorded at a penetration of 2.5 mm to a total penetration of 7.5 mm. Then the penetration load was calculated using a testing machine-calibrated equation and the load-penetration curve was plotted. Finally, the CBR was calculated using corrected load values taken from the load-penetration curves

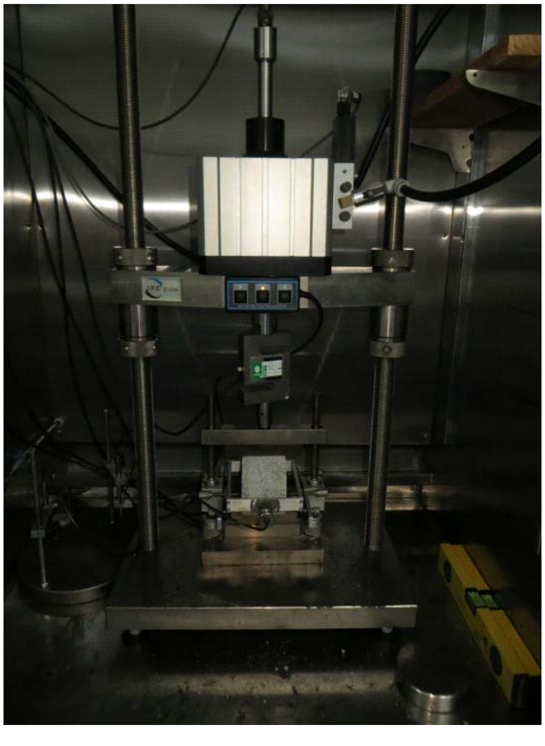

Fig. 4: Indirect tensile resilient modulus testing setup

Fig. 5: Flexural strength testing setup

for 2.54 mm and 5.08 mm penetration by dividing the corrected load by the standard stresses of 6.9 MPa and 10.3 MPa, respectively and multiplying by 100. Figure 6 shows the CBR testing apparatus and the CBR testing setup.

Fig. 6: California bearing ratio testing setup

RESULTS AND DISCUSSION

This section evaluated the short-term performance of stabilized road base by conduction laboratory tests on CRTB and untreated road base materials. Literature review presented in this section is summarized in Table 4, which indicates soil aggregate stabilization with different type of polymers. From the table, it is concluded that there is a little study to show the flexural strength (modulus of rupture) and CBR of the soil aggregate stabilization with the additives. Therefore, this research aims to contribute to filling the gap of soil aggregate stabilization of road base by applying UCS, ITS, ITRM, FS and CBR tests.

Unconfined Compressive Strength (UCS): The results of UCS tests are presented in Fig. 7 and 8.

Figure 7 shows the influence of the Rovene® 4045 content on the UCS for 7 and 28 days of curing. It is seen that an increase in the Rovene® 4045 content caused the UCS of the mixture to increase owing to the presence of both flexible butadiene chains and rigid styrene chains in the SBE molecular structure, the consolidation of which provides good mechanical properties such as increased strength, water tightness and abrasion resistance up to a concentration of 7%. However, at concentrations higher than 7%, the UCS decreased on account of a higher water content of 53.53% of Rovene® 4045. Further, the results of the UCS test reveal that it increased by 30.1 and 98.29% upon the addition of a 4% portland cement-7% Rovene® 4045 mixture as compared to a specimen with only 4% cement after 7 and 28 days of curing time, respectively.

Table 4: A summary of relevant laboratory studies on soil/aggregate stabilized with different additives

Tests	Type of additives mixed with cement	Type of soil	Reference
Toughness test	6 polymer emulsions (called P1-6 respectively), acrylic vinyl acetate copolymers and 3 concentrations of portland cement	Silty-sand	Newman and Tingle (2004)
Susceptibility to moisture, scanning electron microscope	Polyethylene, styrene-butadiene-styrene and starch	Both granular and fine-grained subgrade materials	Rauch *et al*. (2002), Tingle *et al*. (2007) and Al-Hadidy and Tan (2009)
Tensile strength	Synthetic polymer emulsions	Clays	Khattak and Alrashidi (2006) and Anagnostopoulos (2007)
Freezing and thawing test, curing test	Synthetic fluid	Fine-grained soils	Hazirbaba and Gullu (2010)
UCS, toughness, scanning Electron microscope, flexural Strength	Styrene-butadiene rubber emulsion	Fine-grained soils	Wang *et al.* (2005)
Permeability, scanning electron microscope	Styrene Butadiene Rubber (SBR) latex	Aggregate	Yang *et al*. (2009)
Scanning electron microscope, water tightness, abrasion resistance, corrosion resistance, sulfate resistance	Styrene-butadiene rubber	Natural sand (Suez region), natural gravel (Katamya-Cairo)	Shaker *et al*. (1997)
Setting time and consistency in the fresh state and porosity, density, ultrasonic modulus and compressive and flexural strength dynamic compression	Styrene Butadiene Rubber (SBR) Latex	Sand and gravel	Barluenga and Hernandez-Olivares (2004)
Compressive strength, water absorption and resistance improvement to chemical attack and corrosion	Styrene Butadiene Rubber (SBR) emulsion	Lightweight aggregate concrete	Rossignolo and Agnesini (2004)

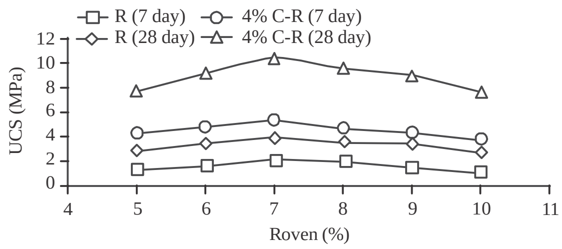

Fig. 7: Plot of UCS vs., Rovene® 4045 content, R: Rovene® 4045 and C: Cement

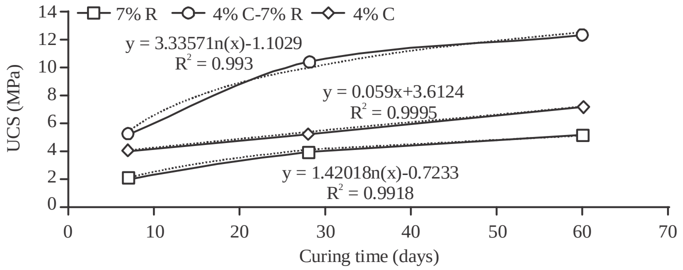

Fig. 8: Plot of UCS vs., curing time

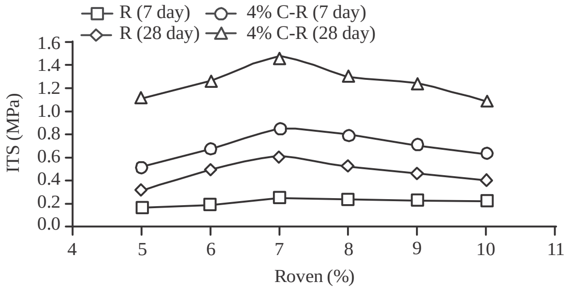

Fig. 9: Plot of ITS vs., Rovene® 4045 content

Figure 8 shows the influence of curing time on the UCS via linear and nonlinear models. In this Figure, it can be clearly seen that the UCS increases with increasing curing time for 4% portland cement, 7% Rovene® 4045 and the 4% cement-7% Rovene® 4045 mixture. The results indicate that the relative compressive strength obtained after curing for 60 days increased by 71.92% upon the addition of a 4% portland cement-7% Rovene® 4045 mixture as compared to a specimen with only 4% cement.

Indirect Tensile Strength (ITS): The results of ITS tests are presented in Fig. 9 and 10.

Figure 9 shows that the tensile strength increases up to a Rovene® 4045 content of 7% and decreases after that because of the same mechanism described in previous section, which also indicates that the optimum Rovene® 4045 content is 7%.

The value of ITS increases with an increase in curing time, which indicates that curing time is an important factor in CRTB as shown in Fig. 10. The results of ITS showed strength increases of 68% due to the addition of 4% portland cement-7% Rovene® 4045 as compared to a sample with only 4% cement. It shows the influence of curing time on ITS using linear models where, Y is ITS (MPa) and x is the time (days). The following Eq. 2, 3 and 4 show the influence of cement content, moisture content, density, Rovene® 4045 content and curing time on ITS, namely, the exponential model, the log-scale model and the ACI model, respectively.

$$S_t(t) = 1.179 \times (C/W) \times D^{8.926} \times e^{-0.004M} \times e^{\left[1-\left(28/t\right)^{0.341}\right]},\ R^2 = 0.980 \tag{2}$$

$$S_t(t) = 1.179 \times (C/W) \times D^{8.926} \times e^{-0.004M} \times e\left[1 + 0.754 \log(t/28)\right],\ R^2 = 0.980 \tag{3}$$

$$S_t(t) = 0.775 \times (C/W) \times D^{8.926} \times e^{0.004M} \times t/\left(5.1 + 0.476 \times t\right),\ R^2 = 0.980 \tag{4}$$

where, C is the cement content (%), D is the dry density (g cm^{-3}), W is the moisture content (%), M is the additive content (%) and t is curing age (days).

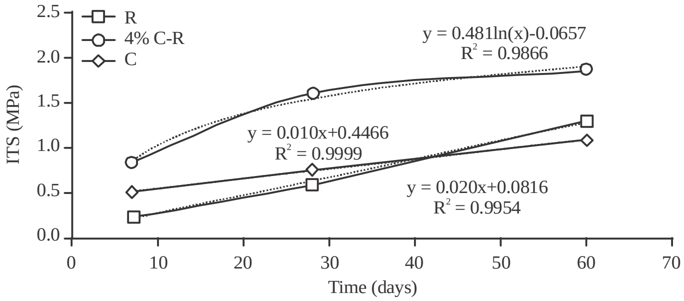

Fig. 10: Plot of ITS vs., curing time

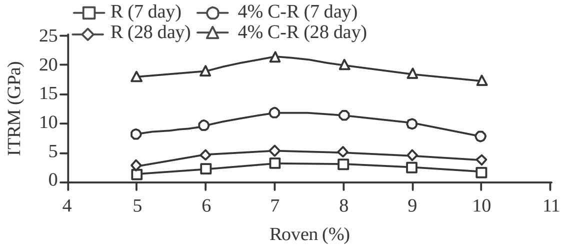

Fig. 11: Plot of ITRM vs., Rovene® 4045 content

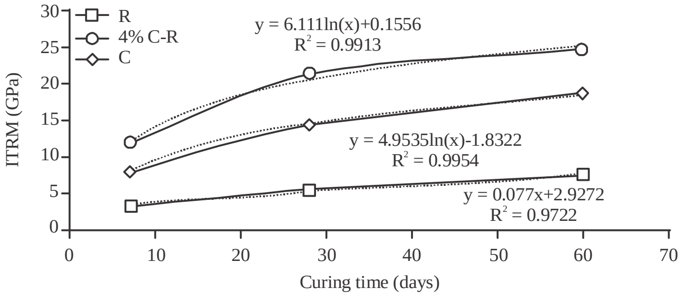

Fig. 12: Plot of ITRM vs., curing time

Indirect Tensile Resilient Modulus (ITRM): The resilient modulus test can be used to assess the relative quality of a mixture for pavement design and analysis. In recent years, based on elastic theory, pavement design methods necessitates the elastic properties of pavement materials as input. The results of ITRM are presented in Fig. 11 and 12.

Figure 11 shows that the ITRM increases until the Rovene® 4045 content reaches 7% and decrease after that, which indicates the optimum Rovene® 4045 content is 7%.

The strength increases with an increase in curing time, which indicates that curing time is an important factor in CRTB as shown in Fig. 12. The results of ITRM test showed strength increases of 32% due to the addition of 4% portland cement-7% Rovene® 4045 as compared to a sample with only 4% cement. It shows the influence of curing time on ITRM using non-linear models where y is ITRM (GPa) and x is the time (days).

Effect on the modulus of rupture: Three samples each of 4% cement, 7% Rovene® 4045 and 4% cement-7% Rovene® 4045 mixture were prepared for testing to determine the flexural strength after 7, 28 and 60 days of moist-curing using a simple beam with a three-point loading method. The FS results are presented in Fig. 13.

Figure 13 shows the values of FS versus days for curing times of 7, 28 and 60 days. The results show that the value of FS increased with increasing curing time, which indicates that curing time is an important factor in CRTB. The use of the 4% cement-7% Rovene® 4045 mixture increased the FS by 48.9% and 225.7% as compared to the use of 4% cement and 7% Rovene® 4045, respectively. The figure also shows the influence of curing time on FS using linear and non-linear models, where, Y is FS (MPa) and x is the time (days). The FS and UCS are critical material parameters as input data for CTB in pavement design methods such as American Association of State Highway and Transportation Officials (AASHTO) and mechanistic-empirical pavement design guide methods (AASHTO., 2004; NCHRP., 2013). In most circumstances, the modulus of rupture is specified by the existing relationship between UCS and FS. For example, in the ACI model,

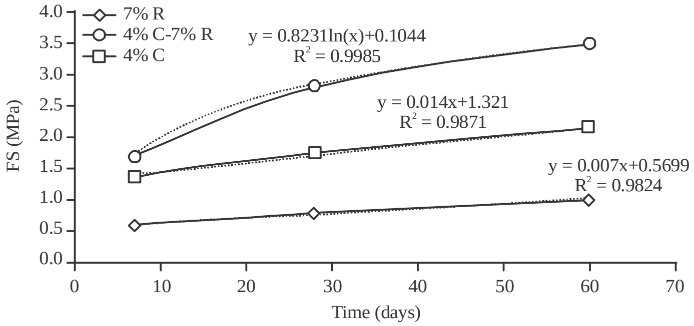

Fig. 13: Plot of FS vs., curing time

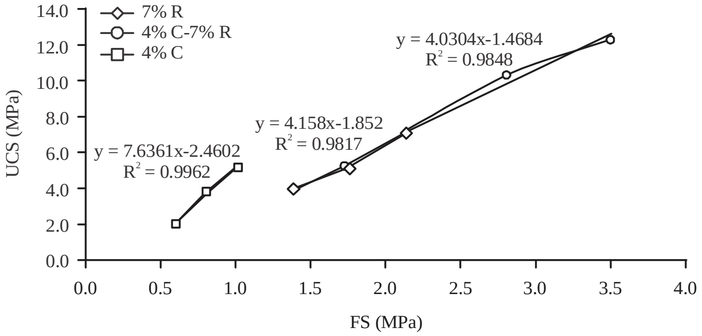

Fig. 14: Relationship between UCS and FS

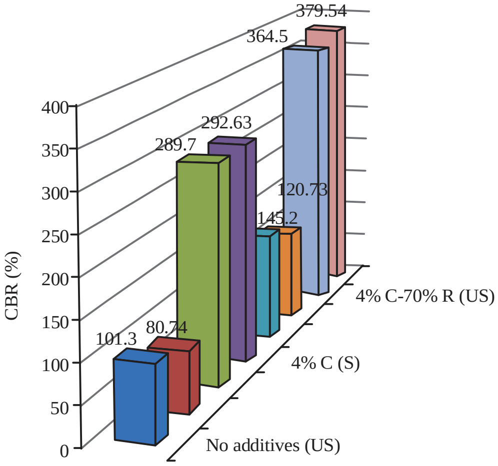

Fig. 15: CBR test results for the mixtures, US: Unsoaked, S: Soaked

whereas in the U.S. Army Corps of Engineers (USACE) model (PCA., 1992) and (El-Maaty Behiry, 2013), where M_{rup} is the modulus of rapture. For the modulus of rupture, it has been shown from previous studies that the FS of CTB is usually about 15-30% of the UCS (Scullion *et al.*, 2008; Garber *et al.*, 2011; El-Maaty Behiry, 2013). Figure 14 compares FS to UCS. The linear models indicate that the average FS of CTB and CRTB for 7-60 days of curing is 32.62 and 29.39% of UCS, respectively.

California Bearing Ratio (CBR): In this study, the improvement of the soil-aggregate was investigated with the inclusion of portland cement only, Rovene® 4045 only and a portland cement-Rovene® 4045 mixture. To express the saturated and unsaturated conditions for different field applications, the CBR was evaluated for soaked and unsoaked samples. The influence of the cement content, Rovene® 4045 content and cement-Rovene® 4045 mixture on the CBR are shown in Fig. 15.

Table 5: Summary of short-term properties obtained from different types of element testing

Curing (days)	Additives	Sample ID	UCS (MPa)	ITS (MPa)	ITRM (GPa)	FS (MPa)	U CBR (%)
7	Tylac® 4190	8% T	1.67	0.22	2.48	0.46	133.4
		4% C	4.05	0.52	7.95	1.39	289.7
		4% C-8% T	5.46	0.98	12.70	1.99	412.2
	Rovene® 4045	7% R	2.10	0.25	3.23	0.60	145.2
		4% C	4.05	0.52	7.95	1.39	289.7
		4% C-7% R	5.26	0.85	11.80	1.72	364.5
	BE	3% BE	0.75	0.16	0.94	0.26	129.2
		4% C	4.05	0.52	7.95	1.39	289.7
		4% C-3% BE	4.42	0.68	9.69	1.50	308.4
28	Tylac® 4190	8% T	3.275	0.49	4.64	0.60	NA
		4% C	5.22	0.75	14.26	1.76	NA
		4% C-8% T	10.92	1.53	23.65	3.26	NA
	Rovene® 4045	7% R	3.85	0.60	5.50	0.81	NA
		4% C	5.22	0.75	14.26	1.76	NA
		4% C-7% R	10.36	1.46	21.23	2.81	NA
	BE	3% BE	1.02	0.25	2.18	0.40	NA
		4% C	5.22	0.75	14.26	1.76	NA
		4% C-3% BE	5.73	1.05	17.69	2.03	NA
60	Tylac® 4190	8% T	4.474	1.01	5.43	0.86	NA
		4% C	7.17	1.09	18.72	2.14	NA
		4% C-8% T	13.96	2.01	27.85	3.88	NA
	Rovene® 4045	7% R	5.20	1.30	7.41	1.01	NA
		4% C	7.17	1.09	18.72	2.14	NA
		4% C-7% R	12.69	1.84	24.72	3.50	NA
	BE	3% BE	1.23	0.34	3.32	0.49	NA
		4% C	7.17	1.09	18.72	2.14	NA
		4% C-3% BE	7.79	1.40	22.33	2.56	NA

T: Tylac® 4190 and BE: Bitumen emulsion, UCS: Unconfined compressive strength, ITS: Indirect tensile strength, ITRM: Indirect tensile resilient modulus, FS: Flexural strength, UCBR: Unsoaked California bearing ratio

The results from samples treated with 4% cement, 7% Rovene® 4045 and the 4% cement-7% Rovene® 4045 mixture are summarized in Fig.15 in terms of CBR performance versus depth of penetration for both unsoaked and 4-day soaked conditions. From the figure, it is clear that the best improvement for both soaked and unsoaked conditions was obtained from the 4% cement-7% Rovene® 4045 mixture. The average CBR of 4% cement, 7% Rovene® 4045 and the 4% cement-7% Rovene® 4045 mixtures are 289.7, 145.2 and 364.5%, respectively, for unsoaked conditions and 292.6, 120.7 and 379.5%, respectively, for the 4 days soaked condition. This result indicates that use of the 4% cement-7% Rovene® 4045 mixture increases the CBR by 25.8% and 150.9% for unsoaked and 29.7 and 214.3% for soaked condition, as compared to the use of 4% cement and 7% Rovene® 4045, respectively. Further, it can be seen from Fig. 15 that the effect of the 4 days soaked condition on the CBR value was negligible for all modified specimens except the samples with no additives, in which the soaked CBR value decreased by 25.4% as compared to the unsoaked condition. In this study, the results of the swelling tests are less than 0.10%, which can be considered negligible. The average swelling potential of the soil-aggregate compaction with no additives at OMC was 0.031%, whereas the average swelling potential of 4% cement, 7% Rovene® 4045 and the 4% cement-7% Rovene® 4045 mixture was 0.0175, 0.0181 and 0.0112%, respectively. This result indicates that the addition of the additives to soil-aggregate samples lowered the swelling potential; however, use of the 4% cement-7% Rovene® 4045 mixtures reduced the swelling potential by 56% as compared to the use of 4% cement. The soil-aggregate used in this study was a low-plasticity silt and it did not present a notable swelling problem even without treatment.

Table 5 outlines the summary of test results obtained from the UCS, ITS, ITRM, FS and U-CBR for short-term performance of CTB and CRTB and shows all the findings of presented study in comparison to previously published studies (Baghini *et al.*, 2014; Baghini *et al.*, 2015a, b). Tylac® 4190 is proposed as a polymer modifier for cement mixtures or tile mortar adhesives. It is a surfactant-stabilized styrene-butadiene copolymer latex used in concrete, mortar, grout and cement mixtures. Bitumen emulsion is a water-based liquid emulsion, which can be used in combination with aggregates with high surface area to provide the desired coating and curing behaviour and is proposed as an emulsion modifier for aggregate-cement mixtures. Comparisons of the tests properties of Cement Bitumen Emulsion Treated Base (CBETB), Cement-Tylac® 4190 Treated Base (CTTB) and CRTB are presented in Table 5. From the Table, it is clear that the best improvement was obtained from CRTB and CTTB.

CONCLUSION

The effects of cement content, Rovene® 4045 content and curing time on the strength of road base material were investigated using a series of UCS, ITS, ITRM, FS and

U-CBR tests to evaluated the short-term performance of the mixture. The strength of the layer increases with higher content of cement and longer curing time. The results of the tests show that with an increase in Rovene® 4045 content, strength increases up to 7% and decreases afterward. The duration of a project can be reduce and project cost may subsequently be reduced by using CRTB. The findings from the tests showed that CRTB is an effective treatment when applied to soil-aggregate in order to improve its strength, Stiffness and increase the bearing capacity of the pavement effectively and consequently, the lifetime of the road will increase as well. In addition, the total roadway layers in CRTB decrease in comparison to conventional variant, which effectively reduces construction time and cost. Based on analysis of the results of this study, the following conclusions are drawn:

- CRTB has good mechanical properties for road base. The results indicate that CRTB produce a good cemented road base with a high load-spreading capacity
- The findings of the present study recommend using 4% cement-7% Rovene® 4045 in pavement base layer as optimum content respectively
- The results show that CRTB increases compressive strength, tensile strength, resilient modulus, modulus of rupture and CBR strength
- The results of UCS, ITS, ITRM, FS and U-CBR tests showed that strength increases of 31, 68, 32, 49 and 26% respectively due to the addition of 4% portland cement-7% Rovene® 4045 as compared to a sample with only 4% cement

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